# School on Strongly Coupled Physics Beyond the Standard Model
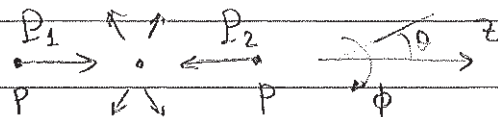
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## Introduction to Collider Physics

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# Introduction to Collider Physics

## I. Introduction

Collider Experiment: e.g. LHC



"Lab frame" $\vec{P_1} + \vec{P_2} = 0$ $\qquad$ $S = (p_1+p_2)^2 = 4E_1^2$

$\sqrt{s} = 2E_1 =$ "c-of-M. energy" $\qquad$ (e.g. 2 TeV @ the Tevatron

$\qquad\qquad\qquad\qquad\qquad\qquad\qquad$ 7 TeV → 14 TeV @ LHC)

After collision: $\underline{detect}$ $\quad e^{\pm}, \mu^{\pm}, \gamma, q/\bar{q}, g, \tau^{\pm}(?)$

$\qquad\qquad\qquad$ ↑ if within

$\qquad\qquad\qquad$ "acceptance" $\qquad\qquad$ → hadrons → jets $\begin{cases} \text{b-tag: } c\tau = 400\text{-}500\mu m \\ \text{c-tag: } c\tau = 100\text{-}300\mu m \\ g\text{ vs }q\text{: maybe} \end{cases}$

$\qquad\qquad\qquad$ + stable, el. charged or colored BSM particles

$\qquad\qquad\qquad\qquad\qquad$ ↑ $c\tau \gtrsim 10\,M \Rightarrow \tau \gtrsim 3 \times 10^{-8}$ sec

cf "natural" lifetime $\tau_M \sim \frac{1}{M} \lesssim \frac{1}{100\,\text{GeV}} \sim 10^{-27}$ sec (for BSM)

$\underline{do\ not\ detect}$ $\quad \nu$ + stable, el. neutral, uncolored BSM particles

$\qquad\qquad\qquad\qquad\qquad$ ↑ ex: WIMP dark matter candidates!

$\underline{measure}$ $\quad E_i, \vec{p}_i$ $\qquad i = 1 .. N_{vis}$ — visible external particles

$\qquad\qquad$ ↑ in some cases, need to use $E^2 - \vec{p}^2 = m^2$.

$\underline{\text{"Event record"}}$: $\mathcal{E} = \{\ \{PID_i, p_i^\mu\}_1,\ \{PID_i, p_i^\mu\}_2, ...\ \}$

En.-mom. conservation: $P_1^\mu + P_2^\mu = \sum_{i=1}^{N} p_i^\mu$

Proton remnant escapes unobserved $\Rightarrow$ useless for $\mu = 3, 0$.

But useful for <u>transverse</u> momentum: $\sum_{i=1}^{N} \vec{p}_i^T = 0$

If this sum is non-zero for visible particles, define

$$\text{"Missing } \vec{p}_T\text{"} \equiv \vec{\not{p}}_T = -\sum_{i=1}^{N_{vis}} \vec{p}_i^T$$

$$\text{"Missing transverse energy"} \equiv \not{E}_T = |\vec{\not{p}}_T|.$$

This is the total mom. of invisible particles, and is the only information available about them.

The goal is to connect $\mathcal{E}$ to "fundamental theory" $\mathcal{L}$

$\mathcal{L} \rightarrow \mathcal{E}$ is algorithmic (at least if pert. theory applies):

$$\mathcal{L} \rightarrow \text{Feynman rules} \rightarrow S \text{ matrix} \rightarrow \frac{d\sigma}{d\Pi}, \quad d\Pi = \prod_{i=1}^{N} \frac{d^3 p_i}{(2\pi)^3} \frac{1}{2E_i} \text{ "phase space"}$$

$$\rightarrow \frac{dN}{d\Pi} = L_{int} \cdot \frac{d\sigma}{d\Pi} \rightarrow \mathcal{E}_{th}: \text{ a realization of this distribution}$$
$$\underset{\uparrow}{\phantom{xx}} \text{(typically generated numerically with a}$$

"integrated luminosity"  "Monte-Carlo generator")
$\propto$ # of collisions
reported by acc. operators

Compare $\mathcal{E}_{th}$ with measured $\mathcal{E} \Rightarrow$ theory OK or ruled out !
(roughly, $\chi^2$ test)

This is all pretty straightforward, but not completely trivial:

— $p$ is composite, $q/g \to$ hadrons — some non-pert. physics enters

— Pert. theory has IR divergences

If deviation from the SM is discovered, we will also need to construct $\mathcal{E} \to \mathcal{L}$ ("the inverse problem"). There is no algorithmic solution. Of course, one can just try many $\mathcal{L}$'s until get a good fit, but need some intuition to know what to try! As usual, intuition comes from collecting and internalizing a set of examples. We will try to do it in these lectures.

## II. Hello World: $Z$ production at the LHC (or Tevatron)

### 1) Parton model
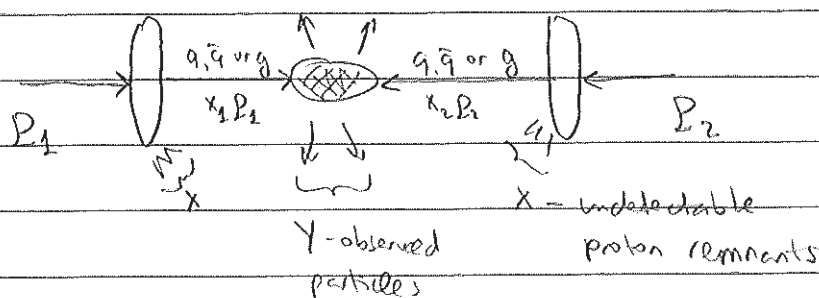


$$\sigma\left(p(P_1) + p(P_2) \to Y + X\right) = \int_0^1 dx_1 \int_0^1 dx_2 \sum_{f_1 f_2} f_{f_1}(x_1, q^2)\, f_{f_2}(x_2, q^2)$$

"parton distribution functions — pdf's"

inclusive —
Sum over all possible X

$$\times \hat{\sigma}\left(f_1(x_1 P_1) + f_2(x_2 P_2) \to Y\right)$$

roughly,
$q^2 = M_Y^2 = M_Z^2$

$f_1, f_2 = u, \bar{u}, d, \bar{d}, \dots, g$     (some refinements are needed — later!)

"Parton frame"  $x_1 \vec{\hat{P}}_1 + x_2 \vec{\hat{P}}_2 = 0$

Parton c-of-m energy:  $\hat{E}_{cm} \equiv \sqrt{\hat{s}} = \sqrt{(x_1 P_1 + x_2 P_2)^2} = \sqrt{2 x_1 x_2 P_1 P_2} = \sqrt{x_1 x_2 S}$
$$\leq \sqrt{S} !$$

Boost lab → parton:  $\hat{E} = \sqrt{x_1 x_2 S} = \gamma(1-\beta) x_1 \sqrt{S} = \gamma(1+\beta) x_2 \sqrt{S}$

$$\Rightarrow \beta = \frac{x_1 - x_2}{x_1 + x_2} , \qquad \gamma = \frac{x_1 + x_2}{2\sqrt{x_1 x_2}}$$

$S$ fixed,  $\hat{s}, \beta, \gamma$  vary event-by-event, according to p.d.f.'s and cross sections.

Facts about pdf's:  — not calculable: reflect non-pert. physics of confinement

— obtained by fits to exp. data (mainly DIS)

$\Rightarrow$ error bars, dep. on $f_i$ and $x$ may be large.

— available at

durpdg.dur.ac.uk/HEPDATA/PDF

[slides, comments on relative importance of $g$, valence/sea quarks]

2) $Z$ prod. : total cross-section

Parton-level, tree-level:  $\hat{\sigma}(gg \to Z) = \hat{\sigma}(qg \to Z) = 0$

$$\hat{\sigma}(q\bar{q} \to Z) = \frac{4}{3}\pi^2 \frac{\Gamma(Z \to q\bar{q})}{M_Z} \delta(s - M_Z^2) \qquad (\text{see P\&S, p.151})$$

$$\Rightarrow \quad \sigma_{LO}(pp \to Z + X) = \frac{4}{3}\pi^2 \frac{\Gamma_z}{M_z} \int_0^1 dx_1 \int_0^1 dx_2 \sum_q 2 f_q(x_1) f_{\bar{q}}(x_2)$$

$$\times \; Br(Z \to q\bar{q}) \cdot \delta(x_1 x_2 S - M_z^2).$$

$X_2$ integral:
$$\int_0^1 dx_2 \, f_{\bar{q}}(x_2) \, \delta(x_1 x_2 S - M_z^2) = f_{\bar{q}}\left(\frac{M_z^2}{S x_1}\right) \cdot \frac{1}{x_1 S} \cdot \theta(x_1 S - M_z^2).$$

$$\Rightarrow \quad \sigma = \frac{4\pi^2}{3} \frac{\Gamma_z}{M_z} \cdot \frac{1}{S} \sum_q \int_{M_z^2/S}^1 \frac{dx_1}{x_1} \cdot 2 f_q(x_1) f_{\bar{q}}\left(\frac{M_z^2}{S x_1}\right) \cdot Br(Z \to q\bar{q}).$$

if $p\bar{p}$ collision, $2 f_q f_{\bar{q}} \to f_q f_q + f_{\bar{q}} f_{\bar{q}}$

since $f_{\bar{q}}^{\bar{p}} = f_q^p$ and vice versa!

Note: $\quad X_{min} = \frac{M_z^2}{S} \approx 2.5 \times 10^{-3}$ @ Tevatron, $1.6 \times 10^{-4}$ @ LHC-7
$$\text{or } 4.0 \times 10^{-5} \text{ @ LHC-14}$$

In general, $X_{min} = \frac{E_{min}^2}{S}$ for a process requiring $\sqrt{\hat{s}} > E_{min}$.

"typical" $X$: $\quad f(x) \cdot f\left(\frac{X_{min}}{x}\right)$ maximal if $x \sim \sqrt{X_{min}}$
$$(\text{rough rule-of-thumb; depends on } \sigma \text{ and other details!})$$

For example, $u\bar{u}$ contribution:
$$x u(x) = \begin{cases} -1.2 - 0.9 \log_{10} X, & 10^{-2} < x < 10^{-3} \\ 0.7, & 10^{-2} < x < 0.1 \\ -0.2 - 0.9 \log_{10} X, & 0.1 < x < 0.6 \\ 0, & x > 0.6 \end{cases}$$

Tevatron: $\quad \int_{X_{min}}^1 \frac{dx_1}{x_1} u(x_1) u\left(\frac{X_{min}}{x_1}\right) \approx 600, \quad \int_{X_{min}}^1 \frac{dx_1}{x_1} \bar{u}(x_1) \bar{u}\left(\frac{X_{min}}{x_1}\right) \approx 5 \quad$ — valence-quarks dominate!

Plug in numbers $\Rightarrow$ $\sigma(pp \to Z) \approx 3$ nb, $u\bar{u}$ alone, LO

Actual $\sigma_{NLO} = 8.2$ nb [slide] not bad!

LHC 14: $\sigma(p\bar{p} \to Z) \approx 60$ nb ($u\bar{u}$ alone, LO) $\sigma_{NLO} = 60$ nb (luck!)
sea quarks dominate; $x \approx \sqrt{4 \times 10^{-5}} \approx 6 \times 10^{-3}$ – in the "sea" range...

[data-slide] HW: Do it for LHC-7

Note: cross section grows with $\sqrt{s}$, due to growth of pdf's at low $x$.

Replace $Z$ with heavy $Z'$ (same couplings):

$$\sigma(pp \to Z'X) = \frac{8}{3}\pi^2 \frac{\Gamma_{Z'}}{M_{Z'}} \cdot \frac{1}{s} \cdot \left[ \underbrace{\int_{M_{Z'}^2/s}^{1} \frac{dx}{x} f_u(x) f_{\bar{u}}\left(\frac{M_{Z'}^2}{sx}\right)}_{F_u(M_{Z'}^2/s)} + \ldots \right]$$

Very roughly, $F_u \approx 0.09 \left(\frac{\sqrt{s}}{M_Z}\right)^3$ ($M_{Z'} \sim 0.1 - 1$ TeV)

Generally $\Gamma_{Z'} \propto M_{Z'} \Rightarrow \sigma \propto M_{Z'}^{-3}$.

3) $Z$ decays and observables

$Z$ decays "promptly"   ($c\tau \ll 1\,\mu m$) $\Rightarrow$ see decay products

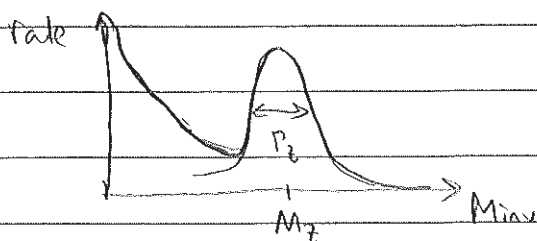Decays:     $Z \to q\bar{q} \to$ jets   $\leftarrow$ invisible: $\sigma(Z) \lll \sigma(jets)$ (plot)
            $Z \to e^+e^-, \mu^+\mu^-$   $\leftarrow$ easily visible! (event display)

"Invariant mass"   $M_{inv} = \sqrt{(p_{\ell^+} + p_{\ell^-})^2}$   is frame-independent
  $\Rightarrow$ compute in parton frame, measure in lab frame.

LO:  $M_{inv} = M_Z$,   $\dfrac{d\sigma}{dM_{inv}} \propto \delta(M_{inv} - M_Z)$

NLO:  Breit-Wigner peak



$\text{Im}\,\Pi \propto \Gamma_Z$ by optical theorem!

$$\frac{1}{p^2 - M_Z^2} \qquad \frac{1}{p^2 - M_Z^2 + i\Gamma_Z M_Z} \quad \text{if } \Gamma_Z \ll M_Z$$
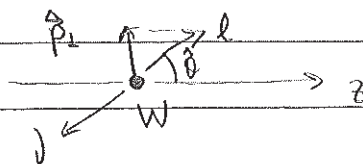
"narrow-width approximation"

  $\Rightarrow \dfrac{d\sigma}{dM_{inv}} \propto \dfrac{1}{(M_{inv} - M_Z)^2 + M_Z^2 \Gamma_Z^2}$



—"inv. mass peak" or "bump"—
Signature of unstable new particle
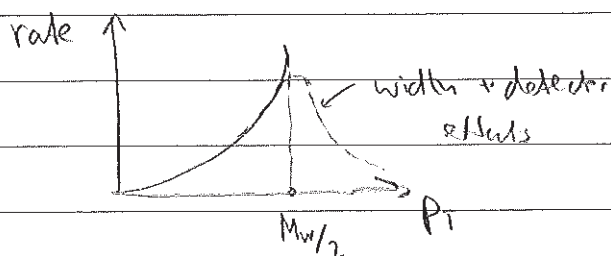[plot]

What if $Z \to W$?     $W \to \ell\nu$ — $p_\nu$ unknown!

• Lepton $p_T$:     partonic c-of-m frame = W rest frame

$$P_T = |\vec{p}_\perp| = |\hat{\vec{p}}_\perp| = \hat{E}\sin\hat\theta = \frac{1}{2}M_W \sin\hat\theta \qquad \Rightarrow \quad P_T^{max} = \frac{1}{2}M_W.$$

$$\frac{d\sigma}{dP_T} = \frac{d\sigma}{d\cos\hat\theta}\frac{d\cos\hat\theta}{dP_T} = \frac{P_T}{\sqrt{\left(\frac{M_W}{2}\right)^2 - P_T^2}}\frac{d\sigma}{d\cos\hat\theta}$$



width + detector effects

"Jacobean peak" [slide]

• "Transverse mass"   $\vec{\hat{p}}_\nu = -\vec{\hat{p}}_{\perp,e} = \vec{\hat{p}}_{\perp,\nu}$

$$M_T^2 \equiv \left(|\vec{p}_\perp^\nu| + |\vec{p}_\perp^e|\right)^2 - \left(\vec{p}_\perp^\nu + \vec{p}_\perp^e\right)^2$$

<u>HW</u>: Show that   $0 \le M_T^2 < M_W^2$

$M_T$ distribution also has a Jacobean peak [slide]

$$\Rightarrow \quad \text{Tevatron} \quad \frac{\Delta M_W}{M_W} \cong \frac{31\,MeV}{80.468} \sim 4\times10^{-4} \text{ best in the world!}$$

Okay, back to the $Z$. Again, parton frame $\rightarrow Z$ at rest.



"Pseudo-Rapidity" $\hat\eta$:

$$\hat{p}_1'' = \hat{p}_1^\perp \sinh\hat\eta_1$$

$$\hat{E}_1 = \sqrt{(\hat{p}_1'')^2 + (\hat{p}_1^\perp)^2} = \hat{p}_1^\perp \cdot \cosh\hat\eta_1$$
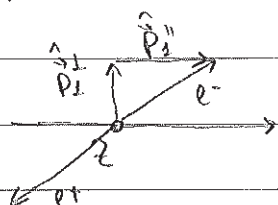
$\hat\eta_2 = -\hat\eta_1$ $\qquad \vec{P} \rightarrow (P'', P^\perp, \phi) \rightarrow (\eta, P^\perp, \phi)$ – canonical description

-8-

Parton → lab frame:  $p^{\perp}, \phi$ invariant

HW: Show that  $\eta_1 = \hat{\eta}_1 + \eta_z,$

where  $\eta_z = \frac{1}{2} \log \left| \frac{s}{M_z^2} x_1^2 \right|$  — independent of $\hat{\eta}_1$, same for all particles — additive Lor. tr. for $\eta$!

$\qquad = \tanh^{-1} \beta$

Likewise  $\eta_2 = \hat{\eta}_2 + \eta_z = -\hat{\eta}_1 + \eta_z$

$\Rightarrow$  $\eta_z = \frac{1}{2} (\eta_1 + \eta_2)$     So, measure $\eta_1, \eta_2 \Rightarrow z$ velocity in lab frame $\Rightarrow$ p.d.f. information.

[slide: NNLO calculation vs. data]

Lab-frame $\eta$ observable:  $p_z^{\shortparallel} = p_1^{\perp} \sinh \eta_1$

$\Rightarrow$  $\tan \theta_1 = \dfrac{1}{\sinh \eta_1}$

$\eta_{max} = \frac{1}{2} \log \left( \frac{s}{M_z^2} \right)$  $= 3.0$  Tevatron  $(\theta_{min} = 5.7°)$
$\qquad\qquad\qquad\qquad\quad\;\; 5.0$  LHC  $(\theta_{min} = 0.8°)$

Detectors designed roughly to cover out to this $\eta$.

"Heavier" final state (i.e. larger $M_{inv}^2 = \left( \sum_{i=1}^{n} p_i \right)^2$)

$\qquad \Rightarrow$ smaller $\eta_{max}$ — more "central"!

Of course, individual particles may have larger $\eta$, may not be detected.

# IV. Radiative Corrections and Infrared Divergences

Naively, subleading orders in pert. theory are only important if you need presision. In reality though, certain aspects of beyond-LO physics must be understood even to develop qualitative intuition about collider processes. The reason is IR divergences.
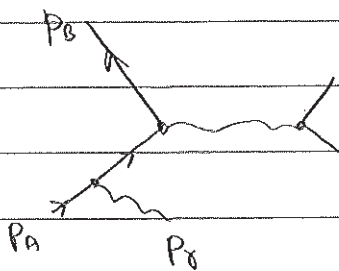
Let's start with a QED example: $e^+e^- \to \mu^+\mu^-$

LO: $\overline{|\mathcal{M}|^2} \propto \alpha^2$

NLO: $\left( \rangle\!\!\sim\!\!\langle \right)^* \cdot \left( \rangle\!\!\sim\!\!\langle \right) + h.c. \quad \propto \alpha^3$ ("loop corr.")

$\left| \rangle\!\!\sim\!\!\langle_{+\ldots} \right|^2 \propto \alpha^3 \quad$ ("real emission")

Let's focus on real emission, one diagram:



$$= \overline{U}_B \gamma^\mu \frac{\not{P}_A - \not{P}_\gamma}{(P_A - P_\gamma)^2} (e\gamma^\nu) U_A \cdot \mathcal{E}_\nu(P_\gamma) \cdot A_\mu$$

$$P_A = (E, 0, 0, E) \qquad P_\gamma = \left( zE, \vec{p}_\perp, \sqrt{(zE)^2 - \vec{p}_\perp^2} \right)$$

$$(P_A - P_\gamma)^2 = -2P_A \cdot P_\gamma = -2zE^2 \left( 1 - \sqrt{1 - \frac{\vec{p}_\perp^2}{(zE)^2}} \right)$$

$\mathcal{M} \to \infty$ when $z \to 0$ "soft singularity"

$\qquad$ or $\quad |\vec{p}_\perp| \to 0$ "collinear singularity"

Physically, soft + collinear photons are unobservable:
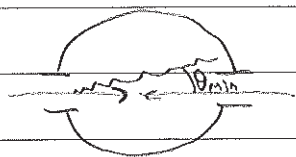


— Small-$\theta$ $\gamma$'s escape through holes
— Small-E $\gamma$'s drowned in "noise"

Define $Q$:
$$p_\perp > Q \quad - \text{observe } 2 \to 3$$
$$p_\perp < Q \quad - \text{observe } 2 \to 2$$

~~Soft p's~~ $\to$ $(p_A - p_\gamma)^2 \to 0$ $\Rightarrow$ $\not{p}_A - \not{p}_\gamma \approx \sum_s u_s(p_A - p_\gamma) \bar{u}_s(p_A - p_\gamma)$

~~Also~~ $\qquad (p_A - p_\gamma)^2 \approx -\frac{p_\perp^2}{z}$

$\Rightarrow \quad \mathcal{M} \approx -\frac{z}{p_\perp^2} \sum_s \left[ e\, \bar{u}_s(p_A - p_\gamma) \not{\gamma}^\nu u_A \varepsilon_\nu^*(p_\gamma) \right] \cdot \mathcal{M}(p_A - p_\gamma, p_B \to p_1, p_2)$

$\underbrace{\phantom{-\frac{z}{p_\perp^2} \sum_s \left[ e\, \bar{u}_s(p_A - p_\gamma) \not{\gamma}^\nu u_A \varepsilon_\nu^*(p_\gamma) \right]}}$

$e \to e\gamma$ amp., ind. of the rest — "factorization"

$$d\sigma_{2\to3} \approx \frac{z\hat{s}}{2s} \, d\Pi_\gamma \left(\frac{z}{p_\perp^2}\right)^2 \underbrace{\sum_s |\mathcal{M}(e \to e\gamma)|^2}_{\displaystyle \frac{4e^2 p_\perp^2}{z(1-z)}\left[\frac{1+(1-z)^2}{z}\right]} \cdot \underbrace{\left|\mathcal{M}_{2\to2}(\hat{s}=(1-z)s)\right|^2 d\Pi_1 d\Pi_2 \frac{1}{2\hat{s}}}_{\displaystyle d\sigma_{2\to2}^{LO}(\hat{s})}$$

$\quad - \text{P\&S pp. 576-578}$

$$d\Pi_\gamma = \frac{d^3 p_\gamma}{(2\pi)^3} \frac{1}{2E_\gamma} = \frac{p_\perp dp_\perp}{8\pi^2} \frac{dz}{z}$$

$\Rightarrow \quad \sigma_{2\to3} \approx \int_{z_{min}}^{1} \frac{dz}{z} \int_{Q}^{\sim E} \frac{p_\perp dp_\perp}{8\pi^2} \cdot (1-z) \cdot \left(\frac{z}{p_\perp^2}\right)^2 \cdot \frac{4e^2 p_\perp^2}{z(1-z)} \cdot \left[\frac{1+(1-z)^2}{z}\right] \cdot \sigma_{2\to2}^{LO}(\hat{s})$

$z_{min} = \frac{Q}{E}$

$\uparrow$

2 log divergences!

-2-

$$\simeq \frac{\alpha}{\pi} \log^2 \frac{\sqrt{s}}{Q} \cdot \sigma_{2\to2}^{LO}(s) + (1 \text{ or } 0 \text{ logs}).$$
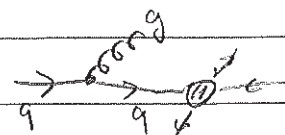
$$\uparrow$$

"Sudakov double log"

$$d\sigma_{2\to2} \simeq \int_0^{z_{lim}} \frac{dz}{z} \int_0^{Q} \frac{dp_\perp}{p_\perp} (..) \sigma_{2\to2}^{LO}(\hat{s}) = \int_0^1 dz \frac{\alpha}{2\pi} \left[ \frac{1+(1-z)^2}{z} \right] \log \frac{Q}{M_e} \cdot$$

$$\uparrow$$
$0 \to M_e$, if you're careful!

$$\times \sigma_{2\to2}(\hat{s} = s(1-z)).$$

This looks like parton model! $e$ beam is really $e\gamma$ beam, with fraction of $\gamma$'s depending on $Q$. Of course, $Q$ is unphysical, so the total rate is idependent of it:

$$\frac{d}{dQ} (\sigma_{2\to2} + \sigma_{2\to3}) = 0.$$

Same thing happens in QCD: e.g.

$$p_{T,g} < Q \implies \text{corrections to p.d.f.'s (Altarelli-Parisi eq's)} \implies f(x,Q)$$
$$p_{T,g} > Q \implies \text{extra jet}$$

If final state $Y$ with inv. mass $M(Y)$ is produced, then

$$\sigma(Y + \text{jet}, p_T > Q) \simeq \frac{\alpha}{\pi} \log^2 \frac{M(Y)}{Q} \cdot \sigma_{LO}(Y \text{ with no jet}) - \text{lots of low-}p_T \text{ jets!}$$

inclusive: $\sigma(Y) + \sigma(Y+\text{jet}) = \sigma_{LO}(Y)(1 + c \frac{\alpha}{\pi})$  (no logs!)

## Soft/Collinear Divergences
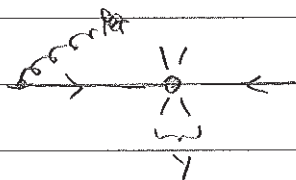


$$p_{T,g} < Q \quad - \text{pdf correction}$$
$$p_{T,g} > Q \quad - pp \to Y + jet$$

$$\frac{\sigma(pp \to Y+jet)}{\sigma(pp \to Y)} \sim \frac{\alpha_s}{\pi} \log^2 \frac{M_{inv}^2(Y)}{Q^2}$$

where $M_{inv}(Y) = \left(\sum_{i=1}^{n} p_i\right)^2$

Ex.: $\quad pp \to Z+j \quad \frac{\alpha_s}{\pi} \log^2 \frac{M_Z^2}{Q^2} \sim 1 \quad$ for $Q \sim 10$ GeV

$\Rightarrow \quad Z$ prod. is typically accompanied by 1 or more 10 GeV jets!

| slide: $p_T^2$ distribution, jet mult. |

Inclusive cross section:

$$\sigma_{inc}(pp \to Y + \geq 0 \, jets) = \int dx_1 \, dx_2 \, f_{f_1}(x_1, Q^2) \, f_{f_2}(x_2, Q^2)$$

$$\times \left[ \sigma_0(f_1 f_2 \to Y) + \sigma_{NLO}(f_1 f_2 \to Y) + \underbrace{\sigma_{LO}(f_1 f_2 \to Y+j, p_T > Q)}_{O(\alpha) \cdot \sigma_{LO}} \right.$$

$$\left. + \dots \right)$$

$\dfrac{d\sigma_{inc}}{dQ} = 0 \quad \underline{\text{but}} \quad f$'s involve "resummation" of leading logs to

all orders in $\alpha$, while partonic $\sigma$ is fixed-order

$\Rightarrow$ cancellation is <u>inexact</u>!

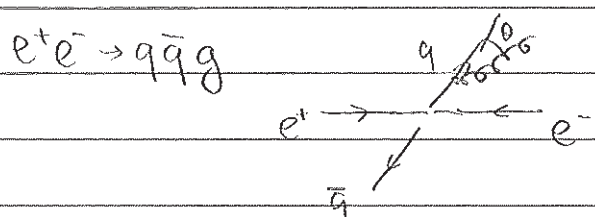Choice of Q: minimize log's in partonic x-section $\Rightarrow Q^2 \stackrel{?}{=} M_W^2(Y)$

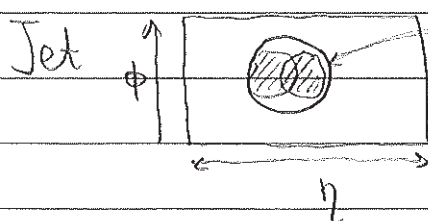Estimate Q dependence: vary up/down by a factor of 2.

## Final State Radiation

$e^+ e^- \to \mu^+ \mu^- \gamma$
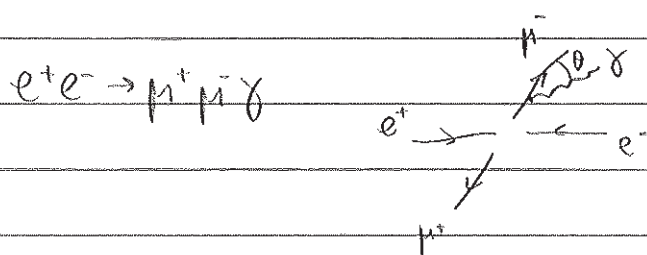
sing.: $E_\gamma \to 0$ (unobs.)

$\theta \to 0$ (cut off by $M_\mu$)

$$\sigma(2 \to 3, E_\gamma > E_{min}) \approx \underbrace{\sigma(2 \to 2)}_{\sigma_0} \cdot \frac{\alpha}{\pi} \log \frac{E_\mu}{E_{min}} \log \frac{E_\mu}{m_\mu}$$

"Sudakov double-log"

$e^+ e^- \to q \bar{q} g$

Same story, but collinear sig. is cut off in a different way:

Jet

"core" $\to$ jet

$q$ and $g$ "merged" for small $\theta$
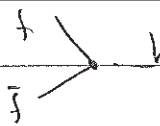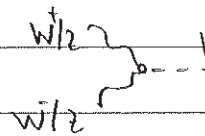
$$\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} < \Delta R_{min} - 1 \text{ jet}$$
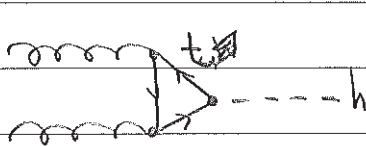$$> \Delta R_{min} - 2 \text{ jets}$$

n-jet rates depend strongly on the details of jet-finding algorithm, very hard to predict; inclusive rates are much safer ("IR-safe observable")
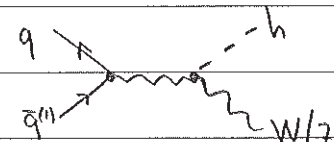
Multiple splittings likely $\to$ PYTHIA, HERWIG, SHERPA
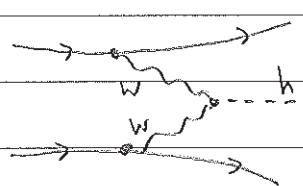"showering codes"

# V. Higgs Search Example
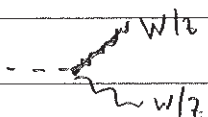
1) Couplings:
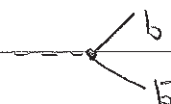


$y_h = \dfrac{M_f}{v} \ll 1$ except $t$



$\sim g v$

2) Processes:  1 h:



"gluon fusion"

$h + W/Z$:



"Bjorken process" or "associated production"

$h + qq$



"Vector Boson Fusion"

[slides: x-sections]

3) Stable? No! Decays:

  if $M_h \gtrsim 2 M_W = 160$ GeV

  $\propto y_b^2$ if $M_h < 2 M_W$

competes with 3-body    for 130–160 GeV

Subdominant modes: $h \to c\bar{c}$, $h \to \tau^+\tau^-$

+ 1-loop induced: $h \to gg$, $h \to \gamma\gamma$

[slide: Br's]

(assume $M_h < 130$ GeV)

4). Backgrounds: $h \to b\bar{b}, c\bar{c}, gg$ completely swamped

[x-sections S vs Bg slide]

$h \to \gamma\gamma$ or $h \to \tau^+\tau^-$ — small Br's, but best S/Bg!

[slides: $h \to \gamma\gamma$ search from CMS]

Note: bump hunting: "shoulder-subtraction" technique
$\Rightarrow$ reduced need for MC,
systematics $\to$ statistics!